X-SAR/SRTM
Part of a Global Earth Mapping Mission

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Abstract

X-SAR/SRTM is Germany's and Italy's contribution to the Shuttle Radar Topography Mission (SRTM), which has been operated from February 12th 2000 to February 21st 2000. It is the X-Band radar interferometer. which operated in unison with SIR-C the C-Band interferometer of the US. Both technique and technology of X-SAR/SRTM will be described as well as both the internal and external calibration procedures. The error sources which influence the product quality will be shown as well as first X-SAR results.

1.Introduction

The Shuttle Radar Topography Mission (SRTM) has been launched on February 2nd 2000 with the Space Shuttle Endevour (STS-99). The 13,6 tons of the payload consisting of 2 interferometric radar systems, a C-Band and a X-Band radar, orbited and mapped the Earth for 11 days. The whole mission mainly was sponsored from the US National Imaging and Mapping Agency(NIMA) as well as from the Italian Space Agency (ASI) and the German Aerospace Centre DLR. [1 to 6] The Mission Objectives were to use C-band and X-band interferometric synthetic aperture radar's (IFSAR's) to acquire data over 80% of Earth's land mass (between 60°N and 56°S) and produce topographic products which meet Interferometric Terrain Height Data (ITHD), specifications: 30 m x 30 m spatial posting with ≤16 m absolute vertical linear accuracy and ≤20 m absolute horizontal circular accuracy at 90%.

The C-Band Radar-Interferometer was an US-Instrument, and the X-Band Radar-Interferometer X-SAR was Germany's and Italy's contribution to SRTM with DLR as the project lead responsible for system engineering, mission operation, calibration and data processing, *Dornier Satellite Systems GmbH* now renamed to ASTRION Co.was the main contractor for the development of the X-SAR flight instrument (X-SAR/SRTM).

Fig.1 shows both the C-SAR and the X-SAR coverage obtained during the eleven day mission. (The colored Fig's 1 - 4 and 7 - 10 are in chap 9).

2. The Shuttle Radar Topography Mission [1, 2, 4, 5, 6]

The two-frequency (C-band and X-band) single-pass interferometric SAR's (Synthetic Aperture Radar) instrument were configured by simultaneously operating two sets of radar

Main mission characteristics

Orbital altitude	233,1 km,
Inclination	57,0 °
Flight duration	11 days, 166 revs
Flight attitude (roll, pitch, yaw)	301°, 180 °, 0 °, ± 0,1 °,
Total payload weight	13405 kg
Total payload power/energy	7,14 kW, 9,8 kW peak/880kWh
Number of data tapes	320 equivalent to 2140 GByte
Crew members	G.Thiele, J.Kavandi, M.Mohri, K.Kregel, D.L.P.Gorie

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antennas, each with a transmit/receive and a receive-only antenna separated by a 60 m baseline and two receiver channels. The 12 meter long and 40 centimeter wide X-SAR main antenna for transmit and receive (channel one) was mounted directly to a tiltable part of the 12 meter C-radar antenna truss structure in the shuttle's cargo bay. The second (receive-only) antenna was 6 meter long and was, together with the second 8 meter long C-band antenna, mounted onto the tip of a 60 meter long, deployable, stiff, boom structure perpendicular to the velocity direction of the space shuttle, to build the baseline. That configuration, the space shuttle with its 60-meter mast extended from the cargo bay was the longest structure ever flown in space.

Fig.2 shows that schematically, **Fig 3** shows a photograph of the deployed mast with both antennas at the end.

3. X-SAR as Part of SRTM, .[1, , 5, 6]

Fig.4 shows the joint operation modes of both systems principally. X-SAR was not capable of operating in a ScanSAR mode like the C–radar which would also allow complete coverage of the Earth during the short orbiting period of 11 days or 166 orbits. X-SAR operated, in turn, in a higher-resolution mode with a smaller swath width of approximately 50 km placed inside the 250km SIR-C scan swath at an angle of 54.5 degrees off-nadir. The C.band and X-band could operate simultaneously or independently. For the most part, they operated together. The only disadvantage to that was that joint operations consumed more power, but since the coverage of sites with both frequencies was desirable, the basic plan took this power usage into account. The advantage is the ability to crosscheck the maps produced by the two systems.

The primary antenna could be tilted in elevation to align its beam with the one of the secondary antenna. To accomplish an azimuth in-orbit alignment of both antennas an electronic beam steering of the receive antenna within a range of 0,9 degrees in steps of 0.3 degrees has been installed. However, it was not necessary to use this equipment during the mission.

The two-channel output data streams, with 90 Mbit/sec, produced by the X-SAR radar were multiplexed for recording on cassette tape recorders onboard or down linked at half the rate. These represent the raw amplitude and phase data for the two images to be processed to create the interferometric fringes on ground after the mission. For X-SAR alone more than 80 hours of data takes have been recorded on 110 cassette tapes.

The X-SAR operated in a higher-resolution mode but with a smaller swath width of 50 km than the C-Band radar. Only approximately 40% of the surface being flown over have been detected. Consequently the selection of the reference target locations is determined by the illuminated swaths of the X-SAR-System. The locations are positioned in regions of swath crossing points. Thus every reference target generally appears in two different SAR images.

Parameter	Main Channel	Secondary Channel
3 dB beam width elevation	5,3°	5,3°
3 dB beam width azimuth	0,14°	0,28°
Electronic beam steering range in azimuth		± 0,9° step 0,03°
Antenna gain	44,5 dBi	41,5 dBi
Noise figure	5,25 dB	2,52 dB
Transmit power peak at HPA output	3300 W	
Pulse length	40 μsec	
Pulse repetition frequency	1674 Hz	
DC power in transmit mode	886 W	290 W
DC power in pause mode	154 W	290 W
Data quantization	4 Bit I&Q	4 Bit I&Q
Data rate	45 Mb/s	45 Mb/s
Total energy	125 KWh	
Total mass	220 kg	123 kg

Tab. 1: X-SAR/SRTM Flight Instrument Characteristics

	X-Band Primary	X-Band Secondary	C-Band Primary	C-Band Secondary
Frequency Polarization	9.6 GHz VV	9.6 GHz V	5.3 GHz H, V	5.3 GHz H, V
Polarization Isolation	39 dB		>25 dB	>25 dB
Adjustable Off-Nadir Angle	15° - 55 ° mechanical	54° -55° mechanical	15° - 55 ° electronical	15° - 55° electronically
Off Nadir during Mission	54.5°	55.5°	36.5°, 46.5°, 53°, 58°	36.5°, 46.5°, 53°, 58°
Adjustable Horizontal Angle	0°	0.9° step 0.3°		
Swath Width	45 km	45 km	225 km	225 km
Azimuth Res. (4 looks)	25 m	25m	30m	30m
Range Resolution 10 MHz/20 MHz Bandwidth	20 m / 10 m	20 m / 10 m	25 m / 13 m	25 m / 13 m
Total Dynamic Range	60 dB	60 dB	60 dB	60 dB
Radiated Peak Power	3.5 kW		1.7 kW	
Main Antenna Area	0.4 m x 12 m	0.4m x 6m	0.7 m x 12	0.7m x 8m
Main Antenna Gain	43.5 dB	41,8 dB	42.8 dB	40,0 dB
Elevation Side Lobe	-20 dB	-21 dB	-18 dB	-19 dB
3 dB Beam Elevat. /Azimuth	5.5° / 0.14°	5,3°/0,28°	4.9° / 0.25°	4,9°/37,5°
Radiometric Resolution	2.5 dB	2.5 dB	1.5 dB	1.5 dB
Data Rate / Channel	45 Mb /sec	45 Mb /sec	45 Mb /sec	Mb /sec

Tab.2 Comparison of X-Band and C-Band flight instruments

4. The Calibration [1, 5, 8]

The accuracy requirements for the mission results claim for an extremely accurate system calibration. In total the SRTM calibration is divided into 5 phases:

1. Preflight concept definition phase including sensor characterization, calibration algorithm development and implementation
2. Ground campaigns during the mission
3. On board calibration measurements during the mission
4. A 6 to 8 month's commissioning phase for the generation of static and dynamic calibration files, and for analysis and modeling of parameter drifts with temperature and time which **is the present status**
5. Operational calibration and validation after the commissioning phase which **will be started at the beginning of next year**

The task of the on-ground calibration was to set up precisely surveyed control targets for both the radiometric and interferometric calibration, 22 calibration fields distributed all over the world have been established.

Hence, in the area from Bayreuth down to Füssen in Bavaria, a calibration field was set up encompassing 27 different locations, in which passive as well as active reference targets (trihedral corner reflectors and/or transponder) and calibrated ground receivers were erected. By using the ground receivers and the transponders, the antenna patterns of both the German-Italian X-SAR-System and the American SIR-C-Radar could be measured, which is required for radiometric calibration. The corner reflectors serve as reference points in the topographic data to calibrate the phase.

Some corner reflectors had to be moved between passes. All had to be pointed towards the shuttle before a pass. Furthermore, it was necessary to determine the geographical location of every corner site very precisely by using differential GPS.

The interferometric calibration concept for X-SAR considers instrument phase calibration and InSAR (Interferometric SAR) imaging geometry calibration also. A height error may result from errors due to uncertainties in the imaging geometry parameters, such as baseline length and tilt angle, and orbit data, and from phase variations caused by the instrument. The tables in **Fig 5** (following page)

X-SAR/SRTM Error Budget

X-SAR/SRTM Height Error Sources

- Baseline Tilt Angle Error
- Baseline Length Error
- Instrument Phase Error
- Random Phase Error
- Ambiguity Phase Error
- Atmospheric Error
- Position Error
- Calibration Error
- Slant Range Error
- Processing Error

Performance Requirements:

- Relative Height Accuracy (90 %) < 6 m
- Absolute Height Accuracy (90 %)< 16 m

Height Error Examples (Middle of Swath)				
	Relative (30 seconds)		Absolute (11-days)	
Error Type	Accuracy	Error	Accuracy	Error
Baseline Tilt Angle	2 arcsec	3,0 m	9 arcsec	13,4 m
Baseline	1,3 mm	0,8 m	4,0 mm	2,6 m
Instrument Phase	4,0 deg	4,2 m	4,0 deg	4,2 m
Total (RSS)	5,5 m		14,4 m	

Fig.5 Error Sources and examples of height errors resulting from special error types

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Calibration Concept

- Estimation of systematic errors
- Monitoring of system parameters and instrument performance
- Characterization of instrument parameters
- Development of calibration models (parameter drifts as a function of time and temperature)
- Ocean as reference height (sea surface height model)

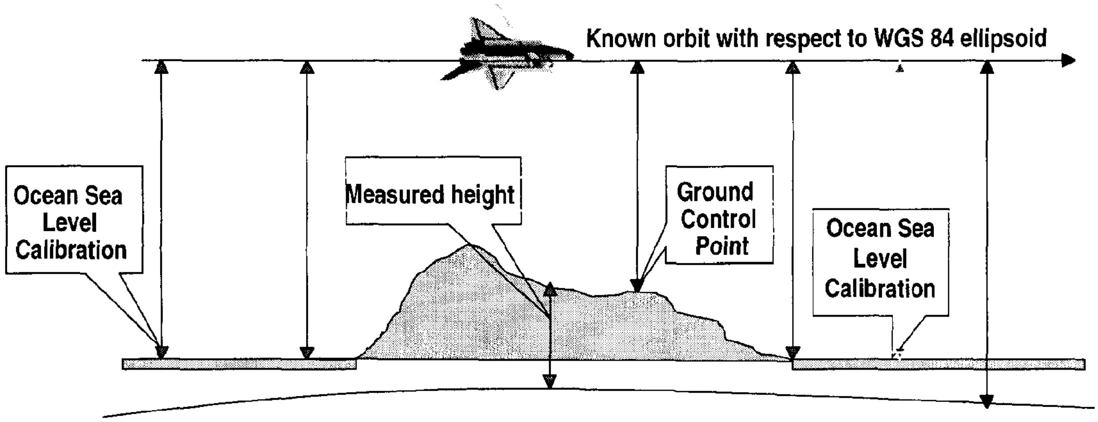

Fig. 6 Scheme of calibration concept

list the main error sources as well as the accuracy requirements which had to be fulfilled in order to reach the goals of the mission with respect to X-Band. A suite of sensors was responsible for measuring and controlling the proper alignment of the secondary antenna with respect to the main antenna and the attitude and position of the interferometric system in orbit.

A star tracker has measured the orientation of the interferometric system in orbit, which is supported by an inertial reference unit consisting of three 2-axis gyros. An optical tracker of the secondary antenna which is a video camera and LED targets, will allow a relative 3-axis measurement of the boom antennas. Additionally, GPS antennas on the secondary antenna structure will provide a 0.8m orbital position accuracy determination and, furthermore, a time reference for the radar with an accuracy of 100 microsec. In addition to the static misalignments, there is the dynamic reaction of the top of the boom to the space shuttle orbit and attitude control system and thermal displacements. An extremely stiff and thermal stable construction is foreseen using CRFP (Carbon Re-inforced Fiber Plastic) technology The ocean surface serves as reference height. Before and after each continental pass, there was a calibration over the ocean (**Fig. 6,** previous page). Phase calibration has to be performed for time and temperature variations. Preflight characterization of the behavior of critical parts is required for estimating the residual calibration error. In certain cases these parameters in combination with temperature measurements can be sufficient for later correction.

5. Products, [1,3,5]

The final products of the SRTM mission arc digital elevation products in a mosaic format generated from C- and X-band radar frequencies. X-band full coverage begins at latitudes greater than about 55° North/South. The C-band radar has completely cover the land surface between 60° North and 58° South with multiple overlap in the higher latitudes.

The complex SRTM data processing will require one to two years in order to convert the raw radar data into topographic maps. Resulting data formats will be compatible with standard cartographic data-analysis software and tailored to the needs of the scientific, commercial and operational user communities.

Detailed specifications of the X- and C-band derived DEM's and other elevation products are delineated in the box on top of the next page. Apart from digital terrain height maps in two different resolutions, there are multi-look images in ground range, single look images in slant range as well as terrain-corrected data and incidence angle masks. A height error map co registered to the elevation maps will be available indicating the quality of the interferometric DEM's pixel by pixel.

The measurement of topography in vegetated regions through SAR techniques causes in some areas deviations from the true terrain height because the short radar wavelengths of C- and X-band (5.3cm and 3.1cm, respectively) sensc thc very top of dense canopies or high buildings. In order to correct for these inconsistencies within the DEM, it is planned to provide a land cover classification map.

6. Results [1,3,5]

During the 11 day mission 69 data takes have been received and analyzed during mission with72 Gigabytes of data, 99 interferogram's and 45 DEM's have been generated. The InSAR processing of a 45 km x 170 km area took 1 hour. The processing was done on a 12 CPU SUN E4000.

Fig .7 shows as the very first result obtained 11 hours after launch the interferometry fringes as well as the resulting (DEM) of an area around White Sands in New Mexico, United States. The DEM is color coded following the rules of normal geographic maps, i.e. increasing altitudes from light brown over dark brown up to white.

SRTM Data Produkts

DTED (Digital Terrain Elevation Data) ⇒ ITED (Interferometric Terrain Elevation Data)

- 1 degree x 1 degree cell; origin in SW corner
- elevations in meter
- intervals in Arc Seconds (DTED 1: posts every 3 arcsec, DTED 2: 1 arcsec)
- datum: vertical = mean sea level, horizontal = WGS 84
- Specification ITED level 2

	C-Band	X-Band	
horizontal absolute accuracy	< 20 m	< 15 m	(90% circular error WGS)
vertical absolute accuracy	< 16 m	< 10 m	(90% linear error WGS)

The **Fig 8** and **Fig 9** show exemplary a DEM of parts of Hokkaido, the northernmost of the four main islands of Japan. With an area 83.500 square kilometers it constitutes more than 20 percent of Japan's land area and comprises 90 percent of Japan's pastureland. The scene shows the northern and southern shores of Ushiura-wan (Volcano Bay). A distinctive feature is the volcano Komaga-take just off the image center on the southern shore of Ushiura-wan. The lower image in Fig. 9 shows a three dimensional representation of the Komaga volcano.

Fig. 10 shows in the upper image a X-SAR DEM as a perspective view over the Baia de Paranagua/Brazil with the Pico Parana in the upper left and in the lower image a photograph of that mountain.

7. Concluding Remarks

The whole Mission was successful and fulfilled the expectations up to 99.6%. The quality of the binary data as well as their homogeneity seems to be excellent [3], however, the final data quality can not yet be accomplished due to missing precision attitude and orbit data The system and the processor as well presently deliver the expected parameters close to the theoretical limits.

8. References

[1] DLR/DFD Homepage
http://www.dfd.dlr.de/srtm/

[2] JPL Homepage: http://www.jpl.nasa.gov/srtm/

[3] Eineder, M.,R.Bamler, N.Adam, H.Breit, S.Suchandt, U.Steinbrecher: SRTM/X-SAR Interferometric Processing-First Results, EUSAR 2000, 3rd European Conference on Synthetic Aperture Radar, 23 – 25 Mai 2000, Munich, Germany,pp 233 -236

[4] T. Farr and M. Kobrick, "The Shuttle RadarTopography Mission: A Global DEM", IGARSS Proceedings 2000.

[5] Werner, M. Shuttle Radar Topography Mission (SRTM)-Mission Overview, Proc. EUSAR 2000, 3rd European Conference on Synthetic Aperture Radar, 23 – 25 Mai 2000, Munich, Germany,pp.209 - 212

[6] Werner, Marian, Kay-Bodo Klein, Martin Haeusler. Performance of the Shuttle Radar Topography Mission, X-Band Radar System

[7] *WERNER, Marian,*Operating the X-band SAR Interferometer of the SRTM

[8] Zink, M., D.Geudtner: First Results from The Calibration of the Interferometric X-SAR System on SRTM, EUSAR 2000, 3rd European Conference on Synthetic Aperture Radar, 23 – 25 Mai 2000, p 223

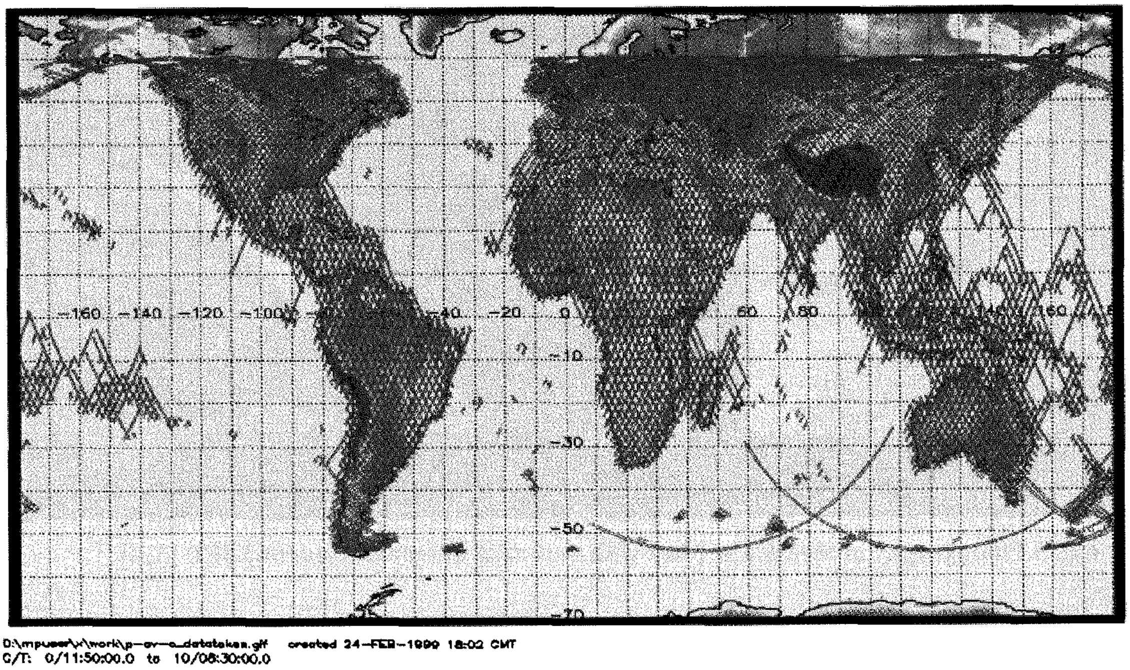

Fig. 1 Coverage Map: X-SAR/SRTM coverage during the 11-day shuttle mission.. The Internet link http://isis.dlr.de/XSAR/srtm will guide you to the geographic locations of the X-SAR swaths.[5, 7]

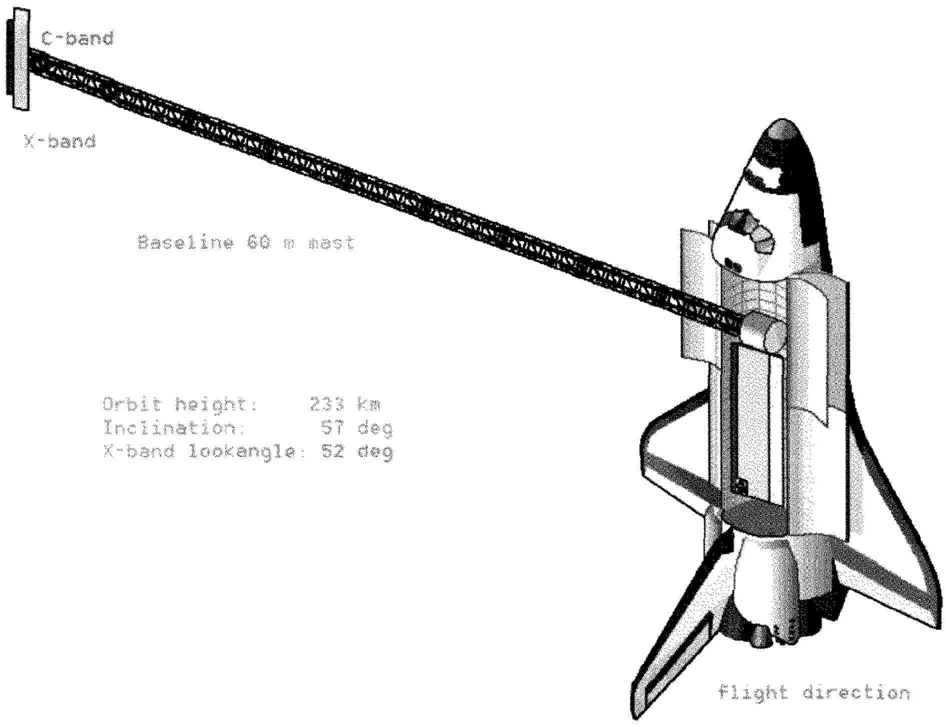

Figure 2: Drawing of the SRTM Configuration with the Secondary Antennas mounted on the Mast

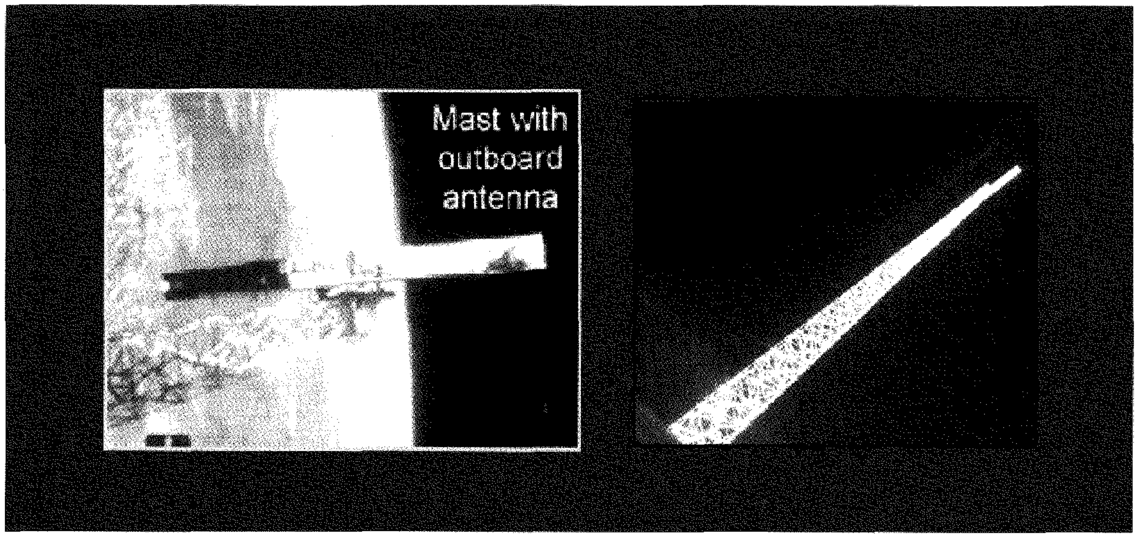

Fig. 3 Photography of the SRTM Mast with outboard antennas, Courtesy JPL [2, 4]

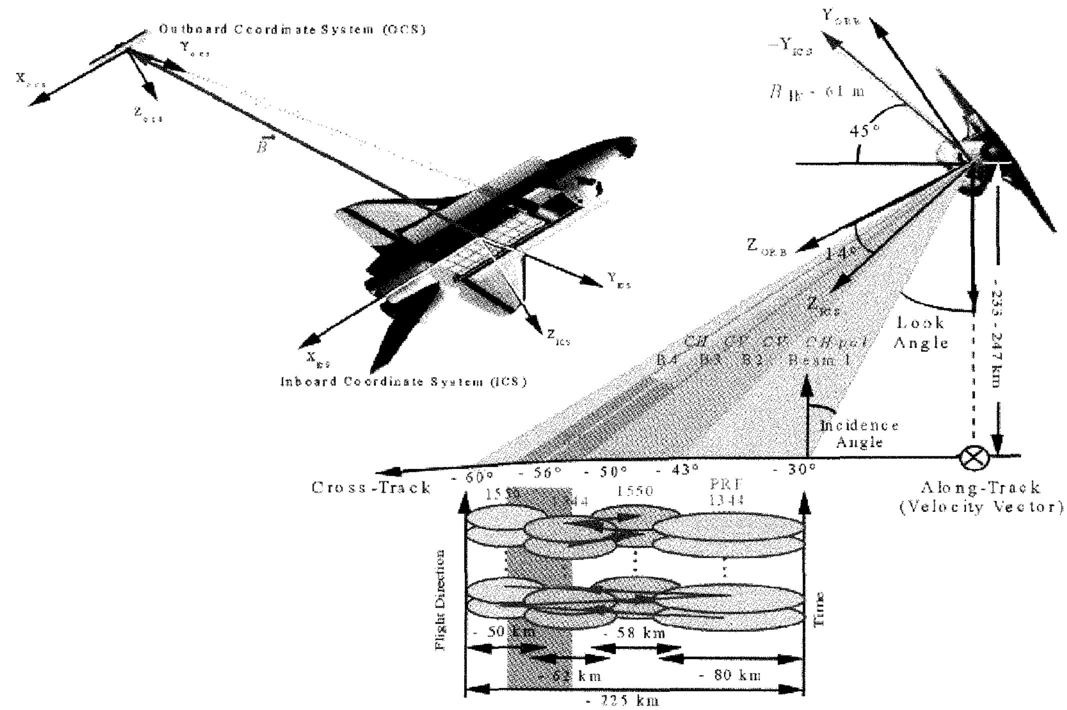

Fig.4 Scheme of SRTM Operation, the ellipsoids represent the C-Band scan swathes, the X-SAR swath is located around 54.5° look angle, Courtesy JPL [2, 4]

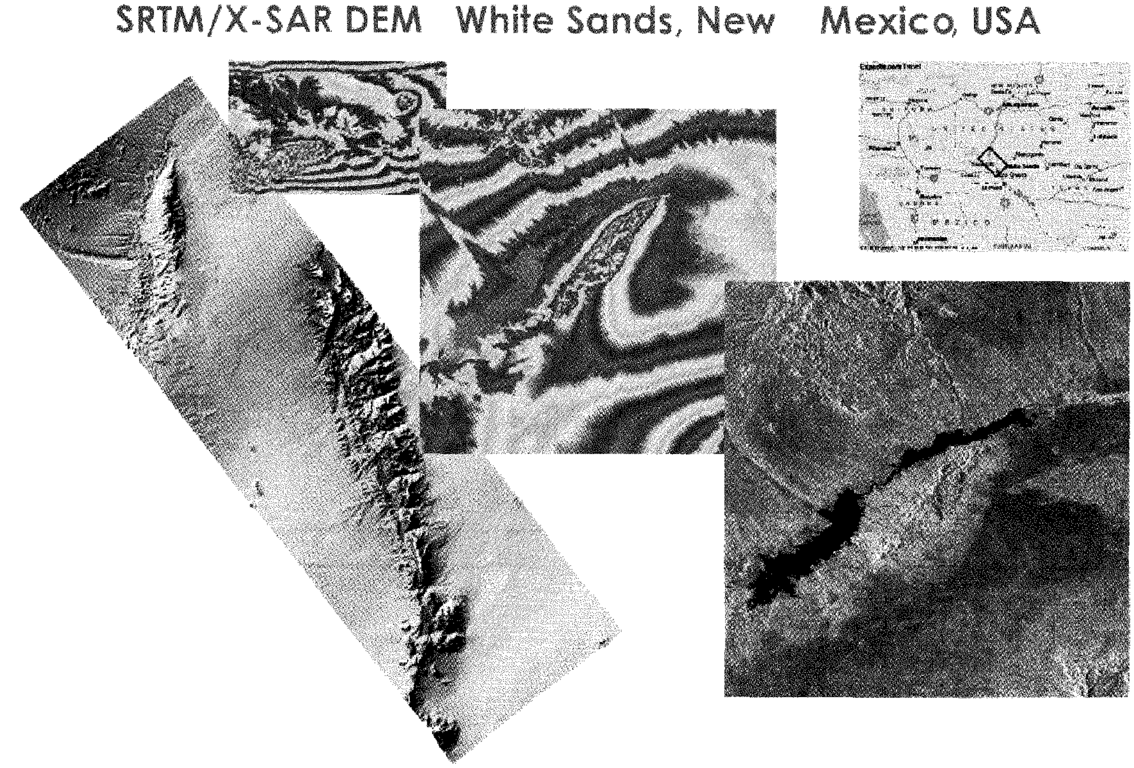

Fig. 7 Fringes, SAR-Image, colorcoded DEM of White Sands, New Mexico, map in the upper right corner [1]

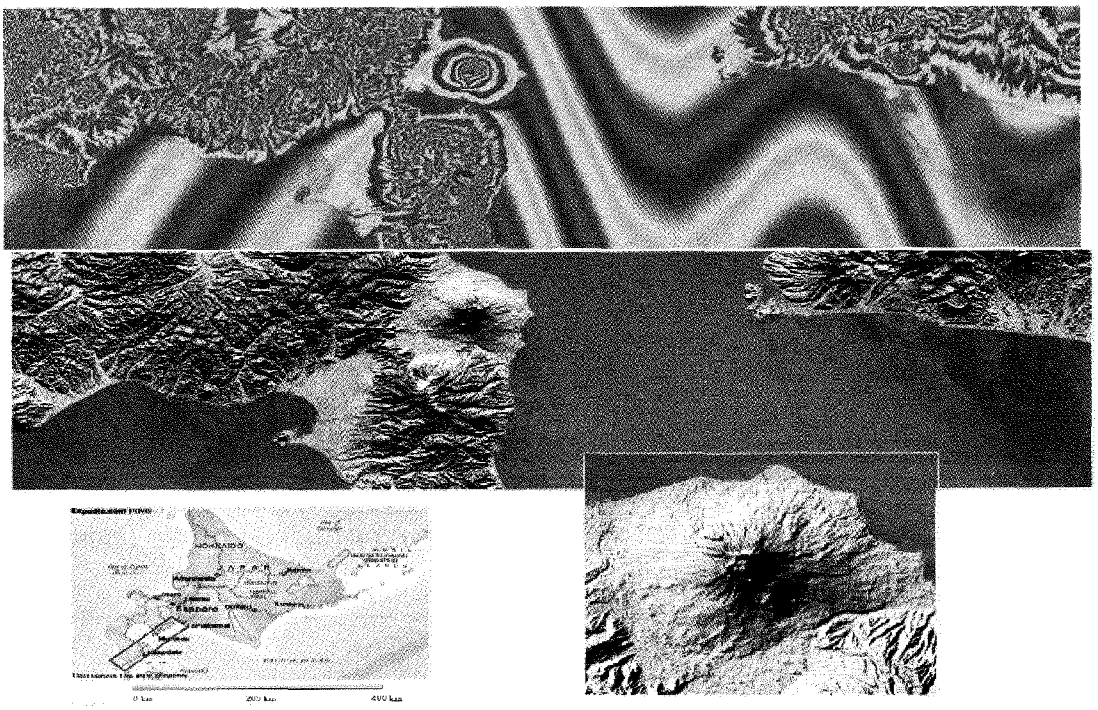

Fig. 8 DEM of Hokkaido Peninsula, Japan, with interferometry fringes with map, enlarged DEM of Kanaka-take Volkano [1]

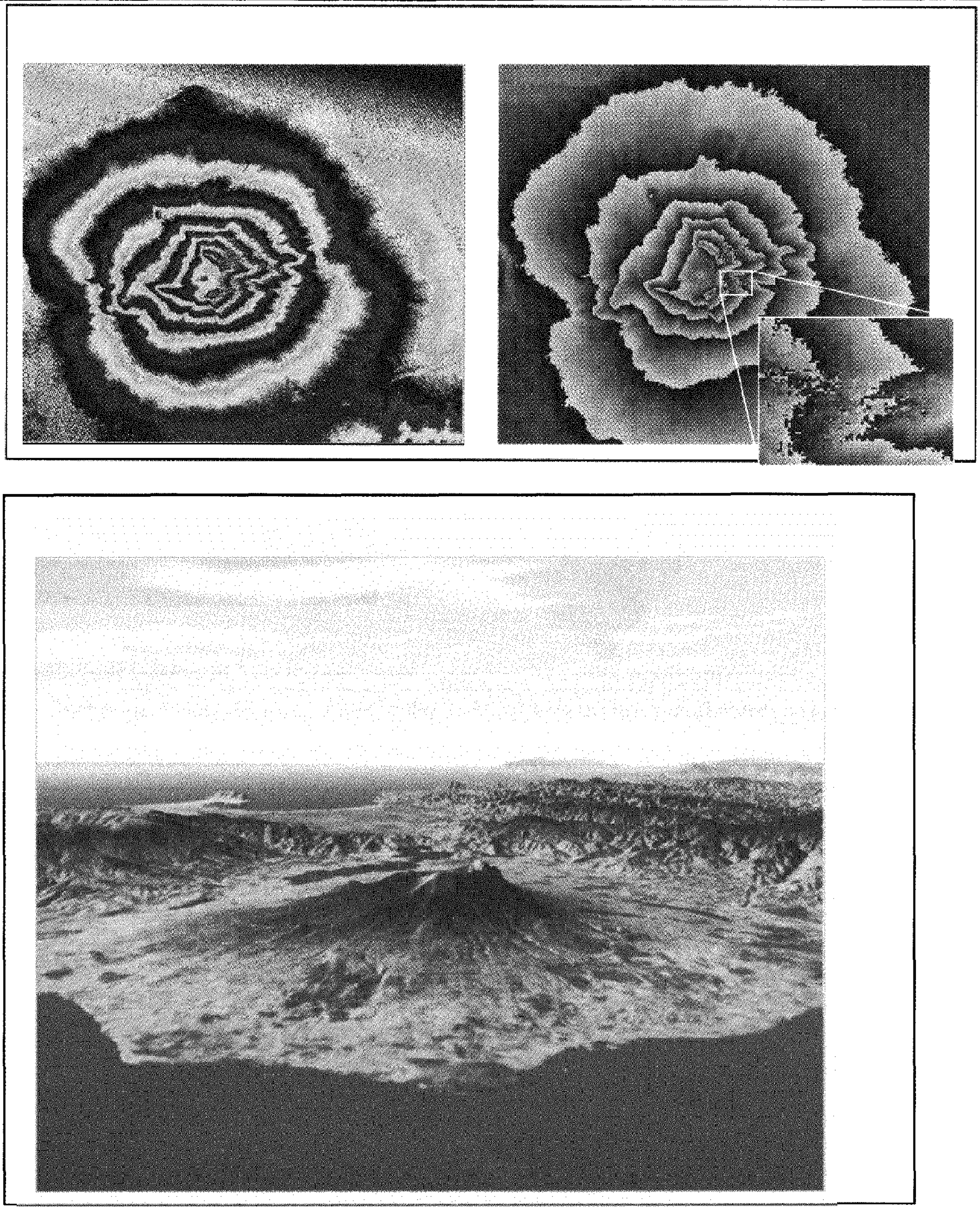

Fig. 9 :Kanaka-take Volkano, Hokkaido Japan: Fringes (upper left), error residua (upper right), 3-D representation (bottom) [3, 1]

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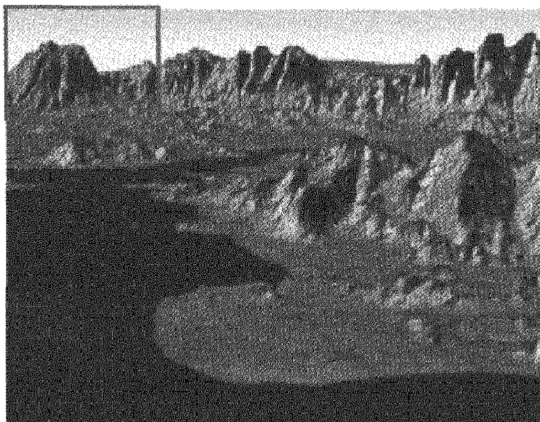

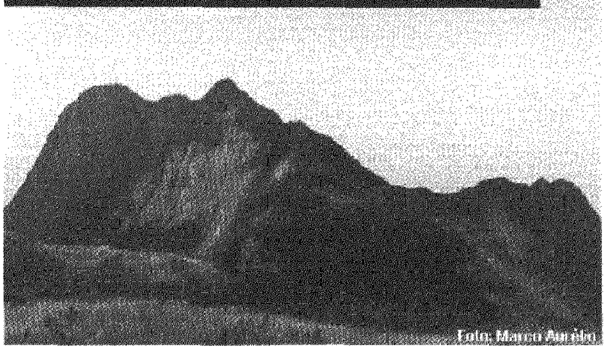

Pico Parana, Paranaguá, Brazil.

Data are recorded over the Baia de Paranaguá/ Brazil, approximately 200km south-east of Sao Paulo located in the State of Paraná Further inland the highest peak of the Serra do Mar Range, the Pico Paraná (1922m) is visible on the upper left corner . The Baia de Paranaguá is an estuary reaching 40km inland and comprises a total area of 667km².

Upper image :perspective view created from the X-SAR DEM over the Baia de Paranaguá towards the mountains in the West.

Lower image: photograph of Pico Parana.

Data Take: 13.02.2000

Scene Center: 48° 36' West, 25° 24' South

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